

On the ^7Li and ^7Be synthesis in novae

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Received _____; accepted _____

Submitted to: ApJ Letters Version: February 1, 2008

ABSTRACT

The production of ^7Li and ^7Be during the explosive hydrogen-burning that occurs in nova explosions is computed by means of a hydrodynamic code able to treat both the accretion and the explosion stages. Large overproduction factors with respect to solar abundances are obtained, the exact value depending mainly on the chemical composition of the envelope. Although the final ejected masses are small, these results indicate that novae can contribute to the ^7Li enrichment of the interstellar medium. Furthermore, since ^7Be decays emitting a gamma-ray (478 KeV), with a half-life of 53.3 days, the synthesis of ^7Li could be tested during the INTEGRAL mission.

Subject headings: novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances — gamma rays: theory

1. Introduction

The origin of lithium and other light elements is still an unsolved problem in astrophysics. It is widely accepted that ^7Li isotopes are produced during the Big Bang and by "spallation" reactions in the interstellar medium by galactic cosmic rays or in flares (see Reeves 1993 for a recent review). Standard Big Bang nucleosynthesis underproduces ^7Li with respect to solar by more than an order of magnitude (see however the recent paper by Deliyannis, Boesgaard & King 1995), whereas spallation reactions by galactic cosmic rays, produce ^7Li and ^6Li simultaneously, as well as ^9Be , ^{10}B and ^{11}B . These two mechanisms are unable to account alone for the present ^7Li abundance ($^7\text{Li} / \text{H} \approx 2 \times 10^{-9}$). Furthermore, they are unable to produce neither the high isotopic ratio $^7\text{Li} / ^6\text{Li}$ observed in the solar system ($^7\text{Li} / ^6\text{Li} = 12.5 \pm 0.2$) nor the $^{11}\text{B}/^{10}\text{B}$ one ($^{11}\text{B}/^{10}\text{B} \approx 4$). Recent measurements of the lithium isotopic ratio in the interstellar medium (Lemoine et al. 1993, Meyer et al. 1993) yield values similar to those found in the solar system, indicating that it has remained nearly constant or even decreased during the last 4.5–5 Gyr. The contribution of a low energy component of the galactic cosmic rays, confined at the source or by stellar flares (Meneguzzi, Audouze & Reeves 1971, Canal, Isern & Sanahuja 1975, Prantzos, Cassé & Vangioni-Flam 1993) can account for the boron isotopes but ^7Li is still underproduced. Therefore, an extra stellar source able to produce this ^7Li without generating ^6Li has to be invoked. The interplay of these sources in the galactic evolution of lithium has been extensively studied (D'Antona & Matteuci 1991, Abia, Isern & Canal 1995).

The synthesis of ^7Li by a stellar source requires the formation of ^7Be which transforms into ^7Li by an electron capture, being ^7Be half-life 53.3 days. As ^7Li is very easily destroyed, ^7Be has to be transported to zones cooler than those where it was formed with a time scale shorter than its decay time. This *beryllium transport* mechanism, as first suggested by Cameron 1955, requires a dynamic situation, like that encountered in asymptotic giant

branch (AGB) stars and novae. Another possibility is the production of lithium and boron isotopes by neutrino induced synthesis, during gravitational supernova explosions (Woosley et al. 1990 and Woosley & Weaver, 1995). The importance of such a mechanism is still a matter of debate (Matteuci, D'Antona & Timmes 1995).

The production of lithium in AGB stars has been extensively studied and these stars represent the unique observational evidence of an autogenic stellar origin, since it has been observed in them (Abia et al. 1991, Abia, Isern & Canal 1993). The huge abundances of lithium found in some AGB stars are a clear proof that these stars are currently injecting important quantities of lithium to the interstellar medium. However it is hard to estimate their total contribution, since it depends on the estimated number of such stars, that are buried by their own wind (Abia, Isern & Canal 1993).

The production of ^7Li in explosive hydrogen burning and, in particular, in accreting white dwarfs exploding as classical novae, was first studied with a parametrized one-zone model by Arnould & Nørgaard 1975. Later on Starrfield et al. 1978 computed the ^7Li yields by means of a hydrodynamic code. This code simulated the explosive stage of novae, without considering the accretion phase, i.e., with an initial envelope already in place. The conclusion of this work was that, depending on the initial abundance of ^3He and on the treatment of convection, ^7Li could be formed in substantial amounts during explosive hydrogen-burning in novae. This problem has been revisited by Boffin et al. 1993. On the basis of an extended nuclear reaction network and of updated nuclear reaction rates, but adopting again a parametrized one-zone model, they showed that ^7Li could only be produced in significant amounts at peak densities lower than 10^3g.cm^{-3} , which are lower than those predicted by hydrodynamic simulations. They argued that the reason of the discrepancy was the neglect of the $^8\text{B}(\text{p},\gamma)^9\text{C}$ reaction in the calculations of Starrfield et al. 1978. However, large overproductions of ^7Be were found by Coc et al. 1995 (using the

semi-analytical model of MacDonald 1983 to obtain the temperature and density profiles and a complete reaction network that included ${}^8\text{B}(\text{p},\gamma){}^9\text{C}$ showing that the origin of the different results was not that reaction. In fact, Boffin et al. 1993 also showed by means of a two-zone approximation that the efficiency of mixing by convection is a very critical parameter, and they stressed the need of a detailed hydrodynamic model to study ${}^7\text{Li}$ production more accurately.

The purpose of this letter is to compute the synthesis of ${}^7\text{Li}$ in both carbon–oxygen (CO) and oxygen–neon–magnesium (ONeMg) novae by means of an implicit hydrodynamic code, that includes a full reaction network, able to treat both the hydrostatic accretion phase and the explosion stage. An estimation of the contribution of novae to galactic enrichment is made, on the basis of the overproductions and ejected masses obtained. The importance of the initial chemical composition of the envelope is analyzed.

The detection of ${}^7\text{Li}$ in novae would confirm our theoretical prediction. Furthermore, the detection of gamma-ray emission at 478 KeV, corresponding to the decay of ${}^7\text{Be}$ to ${}^7\text{Li}$ (half-life 53.3 days) in the early phases of novae by the future mission INTEGRAL would also confirm the thermonuclear runaway model for novae and the nucleosynthesis related to it.

2. Model and results

A one-dimensional, lagrangian, implicit hydrodynamic code has been developed following the techniques described in Kutter & Sparks 1972. The code has been built in such a way as to enable the study of both the hydrostatic accretion phase and the fully hydrodynamic explosion. Detailed nucleosynthesis is obtained by means of an extended reaction network, including 100 nuclei, ranging from ${}^1\text{H}$ to ${}^{40}\text{Ca}$, linked through an up to

date network including more than 370 nuclear reactions (see José 1996 and José et al. 1996 for the details). Concerning the reactions involved in ${}^7\text{Be}$ synthesis, rates are taken from the Caughlan & Fowler 1988 compilation, Wagoner 1969, Descouvemont 1989 and Wiescher et al. 1989. Time-dependent convection is included in the code, since the hypothesis that the convection time scale is always shorter than the nuclear time scale, inherent to time-independent convection, is not always fulfilled. With this method, partial mixing in the convective region is included.

Complete evolution of the accretion and explosion stages of white dwarfs with masses ranging from 1 to $1.25 M_{\odot}$, accreting at a rate of $2 \times 10^{-10} M_{\odot}\text{yr}^{-1}$, with initial luminosity $10^{-2}L_{\odot}$ has been computed. We assume that the infalling material is of solar composition, but that some mixing process (diffusion, shear mixing) mixes it with the underlying CO (for $M=1$ and $1.15 M_{\odot}$) or ONeMg (for $M=1.15$ and $1.25 M_{\odot}$) core. This assumption is based on the current prediction that enhanced CNO (or ONeMg) abundances are required in order to produce a nova outburst and to explain some observed abundances (see Livio 1994 for a recent review, and Prialnik & Kovetz 1995 and Politano et al. 1995, for recent calculations of CO and ONeMg novae, respectively). We want to stress that the problem of the initial composition of nova envelopes is rather complicated and that it is far from being understood in a self-consistent way. Studies of diffusion during accretion onto CO white dwarfs have been carried out (Kovetz & Prialnik 1985 and Iben, Fujimoto & MacDonald 1992), but it is not clear if enough enhancements of heavy elements are obtained in the ejecta. For the ONeMg white dwarfs, these studies are still lacking. Therefore, a compromise is to adopt some percentage of mixing with core abundances. We have adopted a 50% of mixing by mass with core abundances, as was done in the work by Politano et al. 1995.

The chain of reactions leading to the formation of ${}^7\text{Be}$ has been extensively discussed in Boffin et al. 1993. During hydrogen burning, the formation of ${}^7\text{Be}$ proceeds through

$^3\text{He}(\alpha, \gamma)^7\text{Be}$ from the initial ^3He as (p, γ) reactions cannot bridge the $A=5$ gap. It is destroyed by $^7\text{Be}(p, \gamma)^8\text{B}$, followed by either $^8\text{B}(\beta^+)^2\text{He}$ or $^8\text{B}(p, \gamma)^9\text{C}(\beta^+, p)^2\text{He}$. However, at high temperature the photodisintegration of ^8B , $^8\text{B}(\gamma, p)^7\text{Be}$, becomes faster than proton capture on ^7Be . In these conditions, the effective lifetime of ^7Be can become larger than the time scale of the outburst (Boffin et al. 1993). For typical densities at the base of the envelope at the onset of explosion, this would happen only above $T_8 \sim 1$. Below this temperature destruction by $^7\text{Be}(p, \gamma)^8\text{B}$ is efficient. Other destruction mechanisms are $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ and beta decay to ^7Li . Radiative alpha capture on ^7Be is always slower than proton capture as long as photodisintegration of ^8B is not efficient. The half-life of ^7Be (53.3 days) would allow the formation of ^7Li long after the outburst when the cooler envelope would prevent the rapid destruction of this fragile isotope. Since ^7Be is more efficiently destroyed than produced below $T_8 \approx 1$ and since it originates only from initial ^3He , it can only be formed during the outburst if enough ^3He survives the initial phase when the hydrodynamic time scale is much longer than in the explosive phase.

The ^3He found in the envelope originates from the accreted material and from the reaction $^1\text{H}(p, e^- \nu)^2\text{H}$ followed immediately by $^2\text{H}(p, \gamma)^3\text{He}$, which increases slightly the ^3He abundance in the initial phase of accretion. The two major modes of ^3He destruction are through $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ and $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$. $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ is always slower than $^3\text{He}(^3\text{He}, 2p)^4\text{He}$, except at lower ^3He abundances. As noted by Boffin et al. 1993, the latter reaction is responsible for the logarithmic dependence of the ^7Be yield with respect to the initial ^3He abundance above $X(^3\text{He})_{\odot}$. This means that hypothetical higher than solar initial ^3He abundances, related to enriched secondary star envelopes, do not alter dramatically the final ^7Be yields. The results presented in this paper are little affected by nuclear uncertainties as the rates of the reactions of ^3He destruction are precisely known.

For the ONeMg model with $M=1.15 M_{\odot}$, hereafter called ONe model since magnesium

is almost absent (see Domínguez, Tornambé & Isern 1993 and Ritossa, García-Berro & Iben 1996), we show the profiles of ^3He and ^7Be abundances along the envelope for different times starting at the beginning of the accretion phase in figure 1. The corresponding temperatures at the base of the envelope are 10^7K , $2\times 10^7\text{ K}$, $3\times 10^7\text{ K}$, $5\times 10^7\text{ K}$, 10^8K , and the maximum temperature ($2\times 10^8\text{ K}$). An additional model, for which a considerable expansion has already occurred ($R_{\text{wd}} > 10^{11}\text{cm}$), is also shown. Our results indicate that ^3He is destroyed down to abundances between 10^{-6} and 10^{-7} , by mass, at the end of the accretion phase. More specifically, these abundances correspond to the phase during which temperatures are around 10^8 K , allowing the photodisintegration of ^8B to prevent ^7Be destruction (see discussion above). Therefore, the final ^7Be abundances are similar to the ^3He ones at this critical phase. It is important to notice that these values are much higher than those at the burning shell ($\simeq 10^{-9}$ by mass, see figure 1), indicating that one-zone models are unable to provide correct yields. The average mass fraction of ^7Be in the shells that will be ejected and, thus, will contribute to interstellar medium enrichment, is around 10^{-6} . Since all the ^7Li finally produced comes from the decay of ^7Be and as temperatures of our last model are low enough to prevent ^7Li destruction, the final ^7Li yield corresponds to the addition of ^7Be and ^7Li mass fractions in the ejected shells. The final ejected mass is $1.9\times 10^{-5}\text{ M}_\odot$, with a mean abundance of ^7Li by mass of 6.0×10^{-7} . Thus, $1.1\times 10^{-11}\text{ M}_\odot$ of ^7Li would be ejected (see table1).

Concerning the CO cases, ^3He destruction is less pronounced, at the same critical phase, and this allows the synthesis of a larger amount of ^7Be . The corresponding profiles of ^3He and ^7Be are shown in figure 2, for the $M=1.15\text{ M}_\odot$ case. The mean mass fraction of ^7Li is 8.2×10^{-6} (the ejected mass of ^7Li is $1.1\times 10^{-10}\text{ M}_\odot$ and the total ejected mass is $1.3\times 10^{-5}\text{ M}_\odot$). The main reason for the different nucleosynthesis in both cases is that for CO novae the presence of ^{12}C implies that the fast reaction $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$ is dominant during the late accretion phase (whereas the energy production through this

reaction is lower in ONe novae, as they almost lack from ^{12}C). Consequently, the duration of the phase prior to maximum temperature is shorter in CO novae, preventing an efficient ^3He destruction and thus leading to a larger final amount of ^7Be synthesized.

As a summary of our results (see table 1, where additional cases are shown), overproductions of ^7Li with respect to the solar abundances between 100 and 2000 are obtained, depending mainly on the chemical composition of the envelope, which is related to that of the underlying core. It is hard to estimate its real contribution to the ^7Li enrichment in the galaxy, since theoretical models systematically produce ejected masses smaller than the observed ones. For instance, our models typically eject $\sim 10^{-5} \text{ M}_\odot$ while the estimated mass of QU Vul 1984 (which has been invoked as a true "neon nova") is around 10^{-3} M_\odot (Saizar et al. 1992). For an overproduction factor as large as 2000 and a total ejected masses of $\sim 10^{-5} \text{ M}_\odot$ (two orders of magnitude lower than observed for QU Vul 1984), a nova event would produce $\sim 10^{-10} \text{ M}_\odot$ of ^7Li . If we adopt the galactic nova rate of Della Valle & Livio 1994 (20 yr^{-1}) and an age of the galaxy of $\sim 10^{10}$ years, novae should produce at least 20 M_\odot of ^7Li . This quantity is clearly smaller than the estimated present content of ^7Li in the galaxy, $\sim 150 \text{ M}_\odot$, but, given the uncertainties in the ejected mass per event the contribution of novae to the galactic content of ^7Li cannot be ruled out yet. A complete analysis of ^7Li yields by novae and their inclusion in a model of galactic evolution is out of the scope of this paper and will be presented elsewhere.

3. Discussion and conclusions

Our results confirm that nova explosions can produce significant amounts of ^7Li . Overproduction factors as large as 2000 are obtained. Our results are quite different from those obtained from one-zone models (Boffin et al. 1993), as the most important contribution to ^7Li enrichment comes from the external shells, where this element has been

transported by convection from the burning shell.

Comparison with the results of Coc et al. 1995 and Politano et al. 1995 shows that the behavior of ${}^7\text{Be}$ abundances can only be correctly predicted if the evolution of ${}^3\text{He}$ during the accretion phase is accurately followed. It is also necessary to stress that the final results strongly depend on the chemical composition at the onset of the explosion. If the underlying white dwarf is a CO one, the ${}^7\text{Li}$ abundances are about one order of magnitude larger than if the white dwarf is an ONe one.

Since the decay of ${}^7\text{Be}$ to ${}^7\text{Li}$ emits a photon with energy 478 KeV, during a phase in which the envelope is very transparent, this transition could be detected by the future INTEGRAL mission (with a sensitivity around 6×10^{-6} at this energy). The flux of the ${}^7\text{Be}$ decay line is:

$$F(\text{counts.s}^{-1}.\text{cm}^{-2}) = 2.2 \times 10^{-6} \frac{X({}^7\text{Be})}{10^{-6}} \frac{M_{\text{ej}}}{10^{-4} M_{\odot}} \frac{1}{D^2(\text{Kpc})} e^{-t/76\text{d}}$$

For an ejected mass of $10^{-5} M_{\odot}$, with an abundance by mass of $X({}^7\text{Be})=8 \times 10^{-6}$, the ${}^7\text{Be}$ decay line would be detectable just after the outburst only for a nova closer than 0.5 Kpc. But for an ejected mass of 10^{-4} or $10^{-3} M_{\odot}$, more in accordance with observations, the lower limit for the distance would be 1.7 or 5.4 Kpc, respectively. This detection would provide a confirmation of the theoretical models of novae and also ensure that ${}^7\text{Li}$ is produced in these scenarios, encouraging a deep search of this element in novae.

Research partially supported by the CICYT (ESP95-0091), by the DGICYT (PB94-0827-C02-02), by the CIRIT (GRQ94-8001), by the AIHF 95-335, and by the Human Capital and Mobility Programme, (CHGE-CT92-0009) "Access to supercomputing facilities for european researchers" established between The European Community and CESCA/CEPBA".

Table 1: ${}^7\text{Li}$ yields and ejected masses for some nova models

| Comp. | $M_{\text{wd}}(M_{\odot})$ | $\dot{M}(M_{\odot}\text{yr}^{-1})$ | $\overline{X}({}^7\text{Li})$ | $\frac{N({}^7\text{Li}/\text{H})}{N({}^7\text{Li}/\text{H})_{\odot}}$ | $M_{\text{tot}}^{\text{ej}}(M_{\odot})$ | $M_{{}^7\text{Li}}^{\text{ej}}(M_{\odot})$ |
|-------|----------------------------|------------------------------------|-------------------------------|---|---|--|
| CO | 1.0 | 2×10^{-10} | 3.1×10^{-6} | 742 | 2.3×10^{-5} | 7.1×10^{-11} |
| CO | 1.15 | 2×10^{-10} | 8.2×10^{-6} | 1952 | 1.3×10^{-5} | 1.1×10^{-10} |
| ONe | 1.15 | 2×10^{-10} | 6.0×10^{-7} | 143 | 1.9×10^{-5} | 1.1×10^{-11} |
| ONe | 1.25 | 2×10^{-10} | 6.5×10^{-7} | 155 | 1.8×10^{-5} | 1.2×10^{-11} |
| ONe | 1.25 | 2×10^{-8} | 7.9×10^{-7} | 187 | 8.3×10^{-6} | 6.7×10^{-12} |

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Fig. 1.— Profiles of ^{7}Be (upper panel) and ^{3}He (lower panel) abundances along the envelope for different times from the beginning of accretion up to the ejection of the envelope, for a 1.15M_{\odot} ONe novae accreting at a rate $\dot{M}=2\times10^{-10} \text{ M}_{\odot}\text{yr}^{-1}$. The successive models correspond to temperatures at the base of the envelope 2×10^7 (solid), 3×10^7 (dot), 5×10^7 (short dash), 7×10^7 (long dash), 10^8 (dot - short dash), 2×10^8 K (T_{max}) (dot - long dash) plus an additional case, for which a considerable expansion has already occurred, $R_{wd} > 10^{11}\text{cm}$ (short dash - long dash). The upward arrow indicates the base of the ejected shells.

Fig. 2.— Same as previous figure but for a CO nova.



